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Assessment of Surface Fluxes from Numerical Weather Prediction Systems

by

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Abstract

Several centres run weather forecast models. As part of their calculations, these models estimate the surface fluxes of interest to oceanographers. During the 1980s these centres started to archive their estimates of surface fluxes. This introduces the possibility of deriving climatologies of fluxes from the weather forecast archives. This study attempts to assess how useful the archives might be for oceanographers. Surface fluxes for 1993 were extracted from the archives at ECMWF (the European Centre for Medium Range Weather Forecasts) and the UK Met. Office (UKMO). These were compared with each other and with climatology. The fluxes were also used to drive an ocean model to find out what the differences implied for ocean modellers.

Earlier studies had shown that there were large differences between the two sets of model fluxes. By 1993, the grossest differences had been reduced, and qualitatively the fields were similar. Large differences still remained, however. Estimates of solar heat flux differed markedly between the two model system; in the tropics the UKMO fields heated the ocean by 100 W m^{-2} more than those from ECMWF, while at high middle latitudes the UKMO fields gave less heating. The pattern of the net heating of the ocean differed most in the southern hemisphere; the ECMWF fluxes implied that the heating rate of the ocean at southern middle latitudes was greater than in the tropics.

1 Introduction

Ocean circulation is driven by the fluxes of heat, fresh water, and momentum through the ocean surface. One of the challenges for oceanographers is to create global datasets of surface fluxes that are accurate enough for the needs of ocean modellers. For example, the World Ocean Circulation Experiment set an accuracy of 10 W m^{-2} for monthly mean climatological estimates over 10° squares (WCRP, 1988). It is unlikely that surface observations alone will ever be able to define the fluxes to the accuracy needed. Ocean forecast systems, such as FOAM, the Forecasting Ocean Atmosphere Model (Foreman, 1992) need information of surface fluxes that resolve the diurnal cycle.

Weather forecast centres use numerical models of the atmosphere to help produce their forecasts. These Numerical Weather Prediction (NWP) models calculate the surface fluxes as part of their representation of the physics of the atmosphere. During the 1980s the centres started to archive their fluxes for use by ocean modellers. The main priority of those developing the NWP suites was to produce the best atmospheric forecast they could. This was no guarantee that the surface fluxes would be accurate. Burridge and Gilchrist (1989) reported an early comparison of surface fluxes from the European Centre for Medium Range Weather Forecasts' (ECMWF) suite with that of the UK Met. Office (UKMO). That study identified many large differences between the models. It concentrated on comparing the fluxes from the two centres with climatology and with each other. Since then, other studies have been performed (eg Alves, 1990ab) and have extended the comparison to other models (G White, 1993, personal communication). NWP systems are not fixed, their components are being continually updated to improve the forecasts. Conclusions from a comparison of fluxes one year may not be valid for analyses produced in later years.

Comparing the surface fluxes from weather forecast models with climatology can show gross errors in the NWP fluxes. The climatologies themselves have errors, so another way must be found to assess the absolute accuracy of the fluxes. One method is to use the fluxes to drive an ocean model (eg Carrington and Anderson, 1993). Although this shows the response of the ocean model to the fluxes from different sources, the method cannot provide a definitive answer because the ocean model itself has errors.

This paper continues the process of comparing the surface fluxes. It compares surface fluxes for 1993 produced by the UKMO and ECMWF NWP suites. The next section of this paper introduces the principles behind the NWP suites. This is followed by a discussion of the global characteristics of the fluxes from the two NWP suites. Regional differences between the fluxes are then discussed, and following that the impact of the fluxes on an ocean model is described. Finally, the main conclusions are summarised.

2 Weather forecast models and fluxes

2.1 Components of an NWP system

Weather forecast suites consist of several stages. Observations are processed into a form suitable for use by the numerical models; they are also checked for accuracy by applying internal consistency checks and comparing them with each other and with an earlier forecast. The next stage is the analysis, during which the observations are merged with the fields produced by the forecast model. Following this the forecast is made by the forecast model.

2.2 Analysis

Different centres use different techniques for the analysis step. ECMWF use a two stage process: first the observations are combined with the model fields to produce the "analysis". Next, the analysis is processed to produce a starting state for the forecast model that will evolve smoothly, a step known as "initialisation". UKMO use a single step approach in which the changes to the model state introduced by the analysis are introduced gradually during an "assimilation" run of the forecast model.

2.3 Forecast model

Although the details of the ECMWF and UKMO weather forecast models differ greatly, the underlying principles are the same. Meteorologists divide the components of the models into two parts: the "dynamics" that represent

the motions that can be resolved explicitly by the model, and the "physics" that represent small scale processes and "external" factors, such as radiation. Surface fluxes are calculated as part of the "physics". The treatment of surface drag, sensible heat flux and evaporation are similar in most NWP models, although differing in detail. Moist processes within the atmosphere (cloud formation, rainfall) and their interaction with radiation are the aspects over which there is greatest variation. Surface fluxes are sensitive to these calculations.

2.4 Surface fluxes

This study uses the surface fluxes calculated by the NWP models during the early stages of the forecast; the first 24 h for ECMWF fluxes and the first 12 h for UKMO fluxes. This allows the true mean fluxes to be derived (the models calculate the mean fluxes from the values at each time step). Monthly means were extracted from the archives. The fluxes examined were solar radiation, latent heating, sensible heating, long wave radiation and wind stress. The UKMO system also archives the wind mixing energy that is needed by the FOAM ocean model; the corresponding values for integrations using ECMWF fluxes were derived from the wind stress.

Climatological estimates of fluxes used for comparison with the NWP results were taken from Oberhuber (1988) and Hellerman and Rosenstein (1983). Oberhuber's flux estimates do not cover the whole Atlantic, so the model integrations that used climatological fluxes took their values from Esbensen and Kushnir (1981) and Jaeger (1976).

3 Large scale characteristics of the fluxes

This section discusses the global characteristics of the annual mean fluxes. Discussion concentrates on zonally averaged fluxes.

3.1 Solar radiation

Zonally averaged heat fluxes are shown in fig. 1 (regions where values are missing are shown in the graph as having a value of zero). Both NWP systems heat the ocean more that the Oberhuber estimate. In the tropics, the UKMO zonal mean exceeds that of ECMWF by 38 W m^{-2}; in middle latitudes the UKMO heating is less than that from ECMWF, reaching 50 W m^{-2} in the southern hemisphere. Both models show the dip in solar radiation associated with the Inter Tropical Convergence Zone.

3.2 Latent heating

Solar heating of the ocean is largely balanced by the cooling that results from evaporation. Fig. 2 shows the zonal mean latent heat flux from the models and climatology. In middle latitudes in both hemispheres the fluxes from both models agree with each other and with climatology. The models cool the ocean less than the Oberhuber atlas suggests north of 50°N but in the tropics they cool the ocean more than the climatological estimate, the cooling in the ECMWF model being 20 W m^{-2} more than in the UKMO model. At the warm temperatures in the tropical oceans, small differences in the sea surface temperature could result in large differences in the latent heat flux; however, the zonal mean difference between the sea surface temperature analyses in the tropics was less than two tenths of a degree.

3.3 Sensible heat flux

Sensible heat flux is much smaller than the components discussed so far (fig. 3). North of 40°N the two models agree within 3 W m^{-2}, but south of that latitude the UKMO model cools the ocean more that the ECMWF model, by up to 10 W^{-2}. Both models cool the ocean more than the Oberhuber estimate except near 70°N.

3.4 Long wave radiation

Long wave radiation generally acts to cool the ocean (fig. 4). Both models cool the ocean more than the Oberhuber climatology. The ECMWF model values vary less with latitude than the UKMO ones. Equatorwards of 30° the UKMO fluxes cool the ocean more than ECMWF fluxes, but polewards of that the pattern is reversed. This difference between the tropics and higher latitudes is consistent with that for solar heating. Differences in the cloud distribution, and properties of the clouds, in the two models might explain the difference.

3.5 Total heat flux

Fig. 5 shows the total heat flux into the ocean implied by the NWP fluxes. Agreement between the NWP fluxes and the Oberhuber climatology is best between 30°N and 60°N, ECMWF following Oberhuber more closely and producing less cooling of the ocean. The NWP fluxes are in good agreement further north. The two sets of NWP fluxes differ greatly south of 30°N. Where climatological data are more plentiful (north of 30°S) the UKMO fluxes are closest to climatology. The peak in the Oberhuber climatology around 40°S is based on an unrepresentative distribution observations (see, eg, fig. 8). Throughout the tropics the ECMWF fluxes heat the ocean less than the climatology or UKMO fluxes (about 40 W m^{-2} less heating), with heating confined to within 5°of the equator. South of 25°S the ECMWF fluxes heat the ocean, attaining a peak heating that exceeds that in the tropics.

3.6 Meridional heat transport

Arguably the most important characteristic of the surface heat fluxes used to drive an ocean model is the meridional heat flux implied by the total surface heating. If the fluxes were used to drive an ocean model to an equilibrium climate, the model would need to develop a circulation that would allow it to produce heat transport compatible with the applied surface fluxes. Fig. 6 shows the meridional heat transport implied by the NWP models. This was calculated by integrating the surface heat fluxes northward from Antarctica. The magnitude of the transport at the North Pole is a measure of the imbalance in the ocean heat budget in the model. It is clear that the UKMO is in good balance, with an implied heat transport of only 0.13 PW at the pole. The balance in ECMWF is less good.

In both hemispheres the ECMWF fluxes imply an equatorward heat flux from middle latitudes, with an implied transport of 1.6 PW from the North Pole. Not only is the global balance of the UKMO model more reasonable, but the pattern is closer to climatological estimates, with pole ward transport in each hemisphere. The magnitude and shape of the transport implied by the UKMO fluxes is in good agreement with the observational estimates by Hsiung (1985) and Hastenrath (1982). ECMWF fluxes imply heat transport that is worse than in the study of 1984 fluxes by Simonot and Le Treut (1987)

3.7 Wind stress

Fig. 7 shows the zonal mean magnitude of the wind stress produced by the models in comparison with that of Hellerman and Rosenstein. The climatological estimates are greater than those from the NWP models, except over the Southern Ocean, probably a result of the method used to derive the climatological estimate. The zonal mean stress in the UKMO model is weaker than in the ECMWF model almost everywhere. Harrison (1989) suggests that the Hellerman and Rosenstein wind stress in the tropics is too strong.

4 Detailed differences between the fluxes

4.1 Total heat flux

The most significant feature of the heat fluxes for an ocean model is the total heating flux. Fig. 8 shows the heat fluxes from the two NWP models, the difference between them, and the estimate from the Oberhuber atlas. Differences between the two models reflect the pattern seen in the zonal means. New information is added by looking at the full fields. The models differ over the western boundary currents of the northern hemisphere (where differences in the wind fields might be expected to have an impact). In regions where there is strong ocean upwelling (eg in the Pacific off the west coast of South America and in the Atlantic off the west coast of Africa) there is more heating in the ECMWF model. Throughout the western Pacific and Atlantic Oceans the ECMWF model cools the ocean more than the UKMO model; these are regions of active convection, and the convection schemes in the two models are qualitatively different.

4.2 Solar heat flux

Comparing the UKMO and ECMWF fields of solar heat flux (fig. 9) again shows a banded structure, supporting the conclusions from the zonal mean fluxes. Less solar heat reaches the oceans in the UKMO fields in middle latitudes. Taken together with the patterns for the long wave heating rate (not shown) this is consistent with the assumption that differences in the fluxes are strongly influenced by differences in clouds between the two models.

4.3 Latent heat flux

The greatest differences between the latent heat flux calculated by the two models (fig. 10) is found in low latitudes and over the boundary currents. Although the difference field is nearly zonal over the Southern Ocean, further north the UKMO fluxes cool the ocean more than ECMWF ones in the western part of the ocean basins and less in the eastern parts and over the boundary currents.

5 Impact of fluxes on an ocean model

5.1 Ocean model

Monthly mean fluxes from the two models, and from climatology, were used to drive an ocean model. The ocean model was that described in Foreman *et al.* (1994). The starting point for the integrations was the end of a six year integration driven by climatological fluxes. Although the surface temperature and salinity of the model are normally relaxed towards climatological values, temperature relaxation was removed for the tests. The model was run for one year, using the fluxes for 1993.

5.2 Differences between model simulations

Comparing the monthly mean ocean model fields for December 1993 allows the differences between the fluxes to be assessed. These differences are shown in fig. 11. Over most of the ocean, both sets of NWP fluxes resulted in cooler sea surface temperatures than did the climatological fluxes (based on Esbensen and Kushnir, 1981), by up to 10°C. As expected, the UKMO model was closer to the climatological evolution. Differences over sea ice should be ignored because of deficiencies in the model of sea ice used for the integrations.

5.3 Changes from start to end of 1993

Looking at the differences between the integrations using different fluxes cannot determine which set of fluxes is preferable. Looking at the change in temperatures between the start and end of the integration (fig. 12) and comparing them with the observed change in temperatures can differentiate between the fluxes.

ECMWF fluxes cool the tropical ocean, whereas climatological and UKMO fluxes warm the northern tropics. This is a direct response to the surface fluxes. Changes in the southern hemisphere appear to be dominated by the closed boundary condition used in the ocean model, but the smaller cooling by ECMWF fluxes is reflected in the change in sea surface temperature. In the central North Atlantic, all three integrations cool the sea surface temperature. It is probable that this results from inadequate heat transport by the North Atlantic Drift, a common problem with ocean models of this resolution. In the Caribbean the UKMO fluxes result in over 5°C heating.

Over the Gulf Stream region all three integrations warm the water. This is consistent with the observed temperature change (reflecting in part the annual cycle of sea surface temperature), but the model integrations warm the water by about 5°C more than in reality.

It is not clear from a single year of integration how much of the difference in sea surface temperature is a transient response to the change in fluxes. In the UKMO integration, for example, it is tempting to hypothesise that the tongue of cool water along 15°N might enter the Caribbean and reduce the excessive heating. Longer integrations are needed to explore the dynamic response further.

6 Summary

6.1 Surface fluxes

Comparing the surface fluxes from the ECMWF and UKMO operational models shows that there is more cooling of the tropical ocean in the ECMWF fluxes than in the UKMO fluxes. ECMWF fluxes heat the ocean more in southern middle latitudes than they do in the tropics. Calculating the implied northward heat transport in the ocean suggests that the UKMO fluxes are preferable. The cause of the differences in fluxes cannot be determined from the data examined. The UKMO model fluxes similar heat transport by the ocean to observational estimates.

6.2 *Model simulation*

All three integrations of the ocean model had similar trends. It appears that the ocean model is unable to supply enough heat to the central N. Atlantic, with the result that it cools. The closed southern boundary appears to have a large scale impact on the flow in the S. Atlantic, even after one year. Future assessments of model fluxes should use an ocean model with more realistic boundary conditions, and run for longer than one year. When used to drive the ocean model, ECMWF fluxes unrealistically cool the ocean throughout the tropics, and UKMO fluxes heat the Caribbean excessively.

6.3 *Future of NWP fluxes for oceanography*

A major difference between the UKMO and ECMWF NWP systems is that the UKMO uses the "Unified Model". This was designed for use as both a weather forecast model and as a climate model to be coupled to an ocean model, whereas the ECMWF model was primarily intended for weather forecasting. As a result, the surface heat budget of the UKMO model has been a major test of the model's acceptability when run in climate mode. The near balance of the total surface heat budget is a symptom of this. There has been less incentive for ECMWF to constrain the surface energy budget of their model. Until ECMWF are able to introduce a better constraint on their surface heat budget, the ECMWF fluxes will be of limited use for ocean climate modellers.

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Figure captions

Figure 1 Zonal average of the annual mean solar heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

Figure 2 Zonal average of the annual latent heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

Figure 3 Zonal average of the annual mean sensible heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

Figure 4 Zonal average of the annual mean long wave radiation flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

Figure 5 Zonal average of the annual mean total heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

Figure 6 Zonal average of the annual mean northward heat transport by the ocean calculated from the UKMO and ECMWF NWP surface fluxes for 1993. Also shown are the observational estimates of Hastenrath (1982) and Hsiung (1985).

Figure 7 Zonal average of the annual mean magnitude of the wind stress at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Hellerman and Rosenstein (1983) climatology.

Figure 8 Annual mean total heat flux for 1993. (a) UKMO, (b) ECMWF, (c) ECMWF minus UKMO, (d) Oberhuber (1988) climatology. The contour interval is 50 W m^{-2}. Shading for the difference between the fluxes is from -200 W m^{-2} to 200 W m^{-2}, and for other fields from 0 W m^{-2} to 300 W m^{-2}.

Figure 9 Annual mean solar heat flux for 1993. (a) UKMO, (b) ECMWF, (c) ECMWF minus UKMO, (d) Oberhuber (1988) climatology. The contour interval is 50 W m^{-2}. Shading for the difference between the fluxes is from -200 W m^{-2} to 200 W m^{-2}, and for other fields from 0 W m^{-2} to 300 W m^{-2}.

Figure 10 Annual mean latent heat flux for 1993. (a) UKMO, (b) ECMWF, (c) ECMWF minus UKMO, (d) Oberhuber (1988) climatology. The contour interval is 50 W m^{-2}. Shading from -200 W m^{-2} to 200 W m^{-2}.

Figure 11 Differences in mean December 1993 sea surface temperatures between one year integrations driven by: (a) UKMO fluxes and climate fluxes, (b) ECMWF and UKMO fluxes, and (c) ECMWF and climate fluxes. Contour interval is 1 K.

Figure 12 Difference between December 1993 mean sea surface temperature and the sea surface temperature at the start of the integrations (1st January): (a) UKMO fluxes, (b) ECMWF fluxes, (c) climatological fluxes. Contour interval is 1 K.

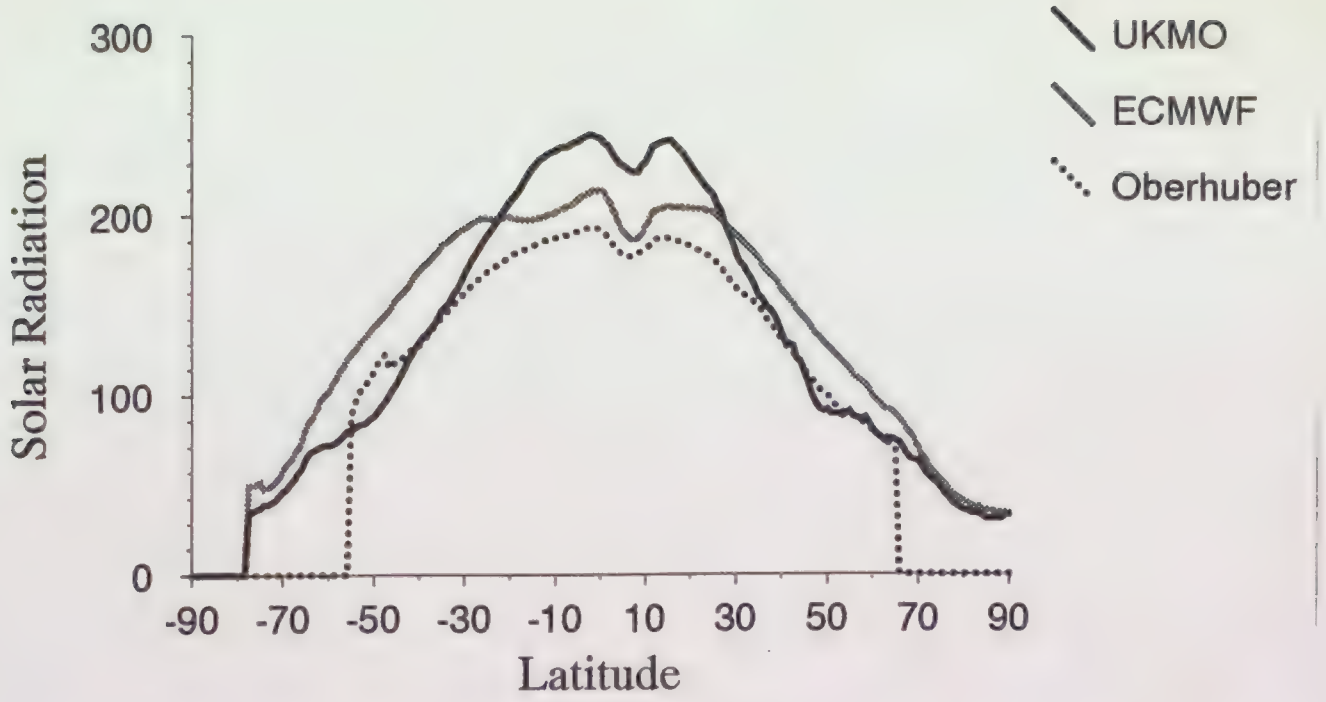


Figure 1 Zonal average of the annual mean solar heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

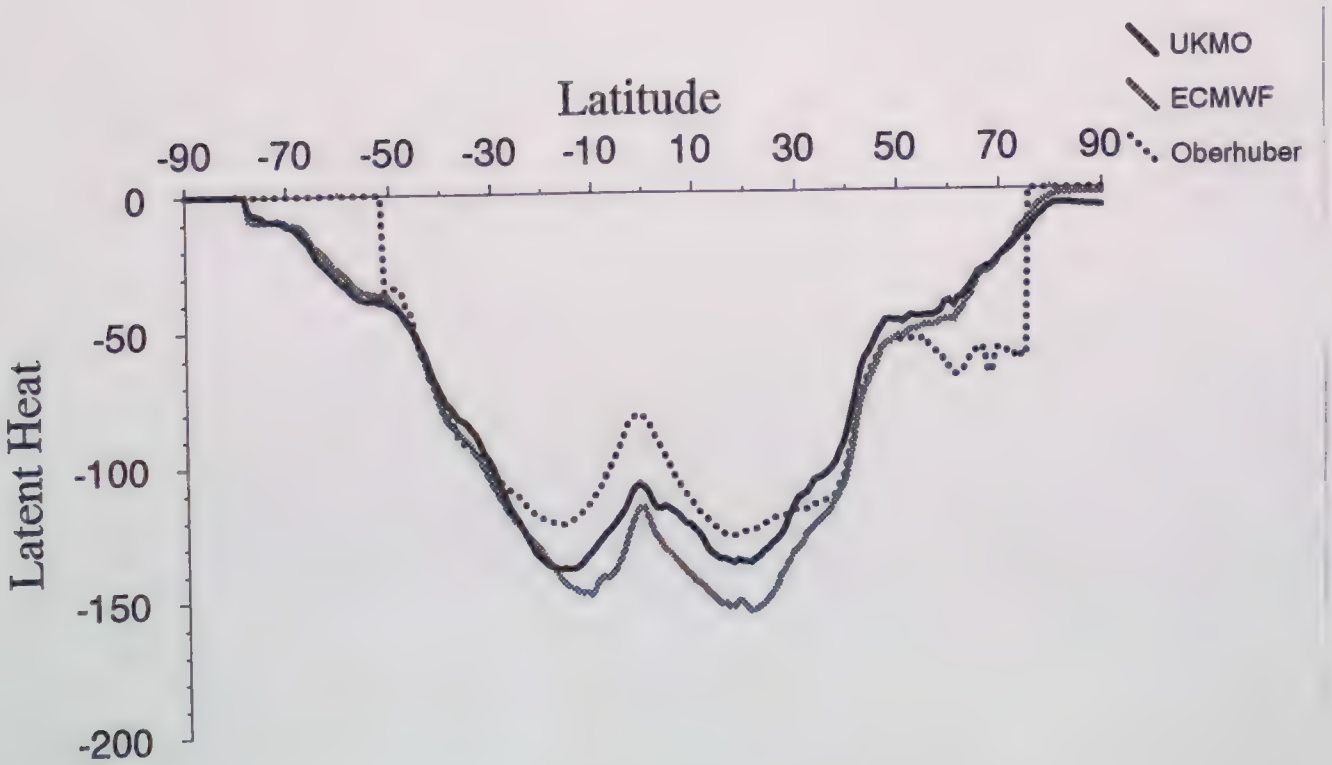


Figure 2 Zonal average of the annual latent heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

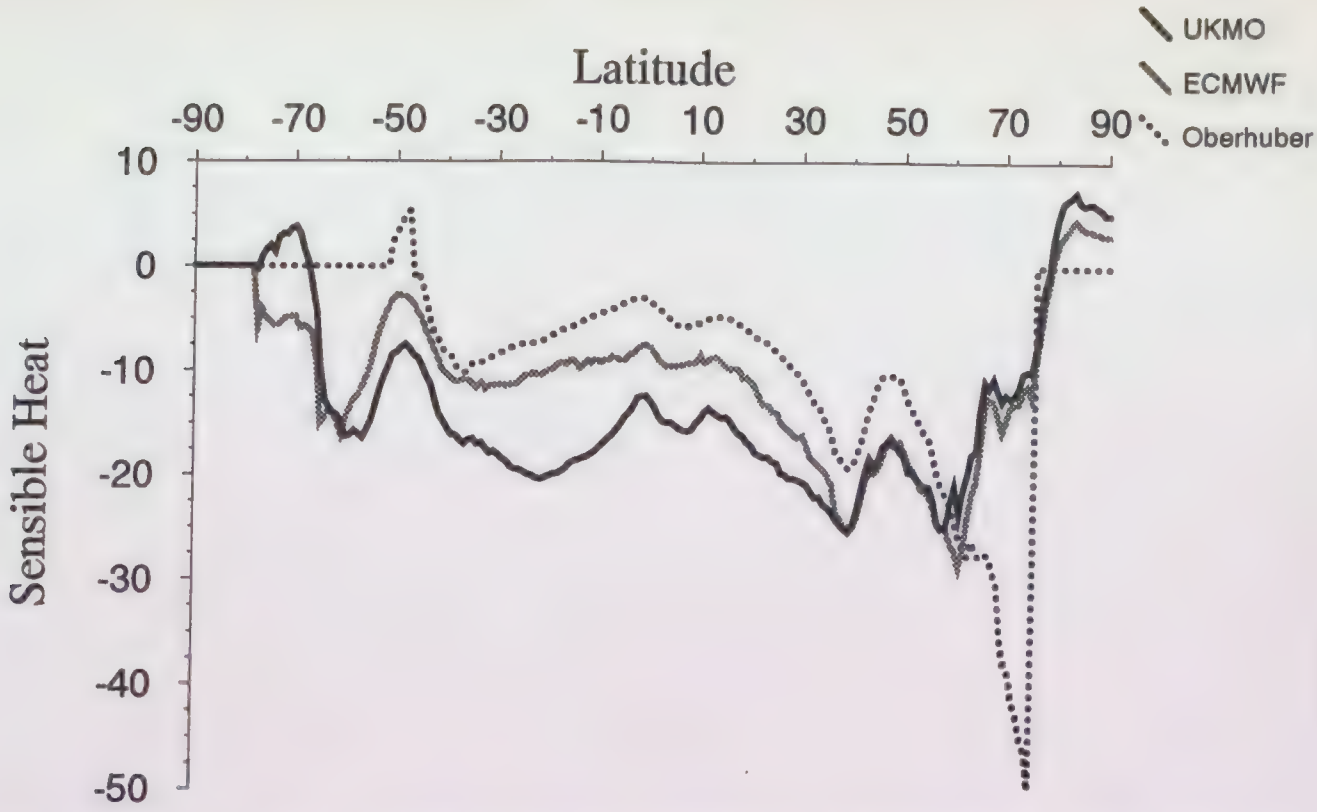


Figure 3 Zonal average of the annual mean sensible heat flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.

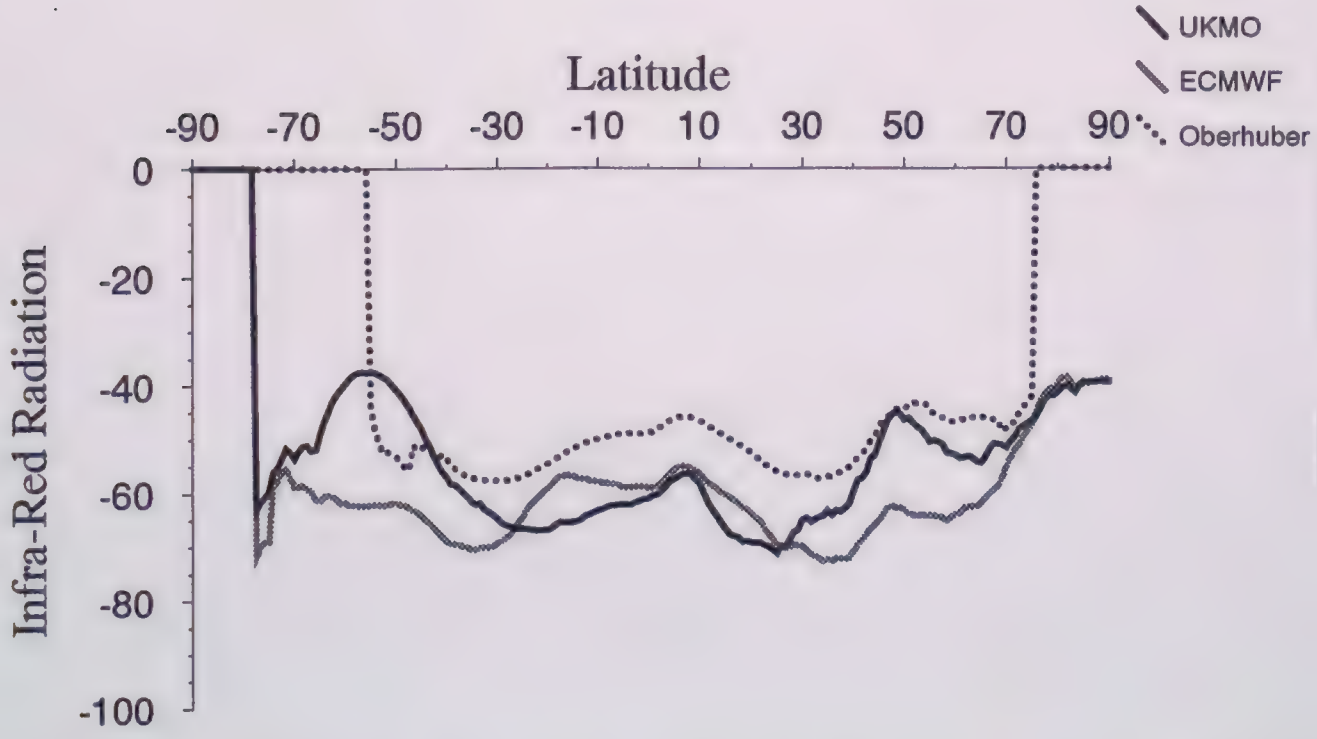
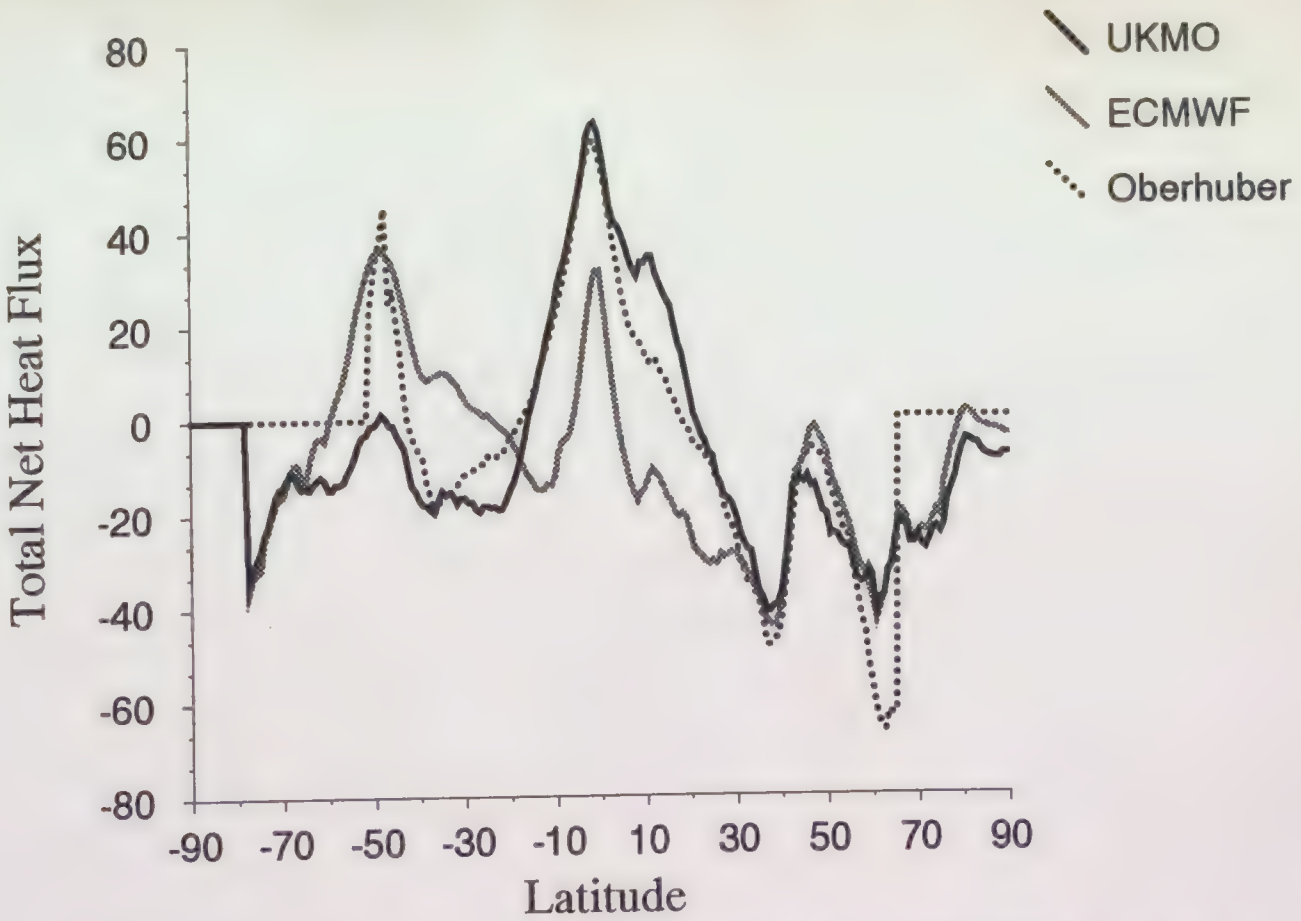


Figure 4 Zonal average of the annual mean long wave radiation flux at the ocean surface for 1993 from the UKMO and ECMWF NWP models and the same quantity from the Oberhuber (1988) climatology.



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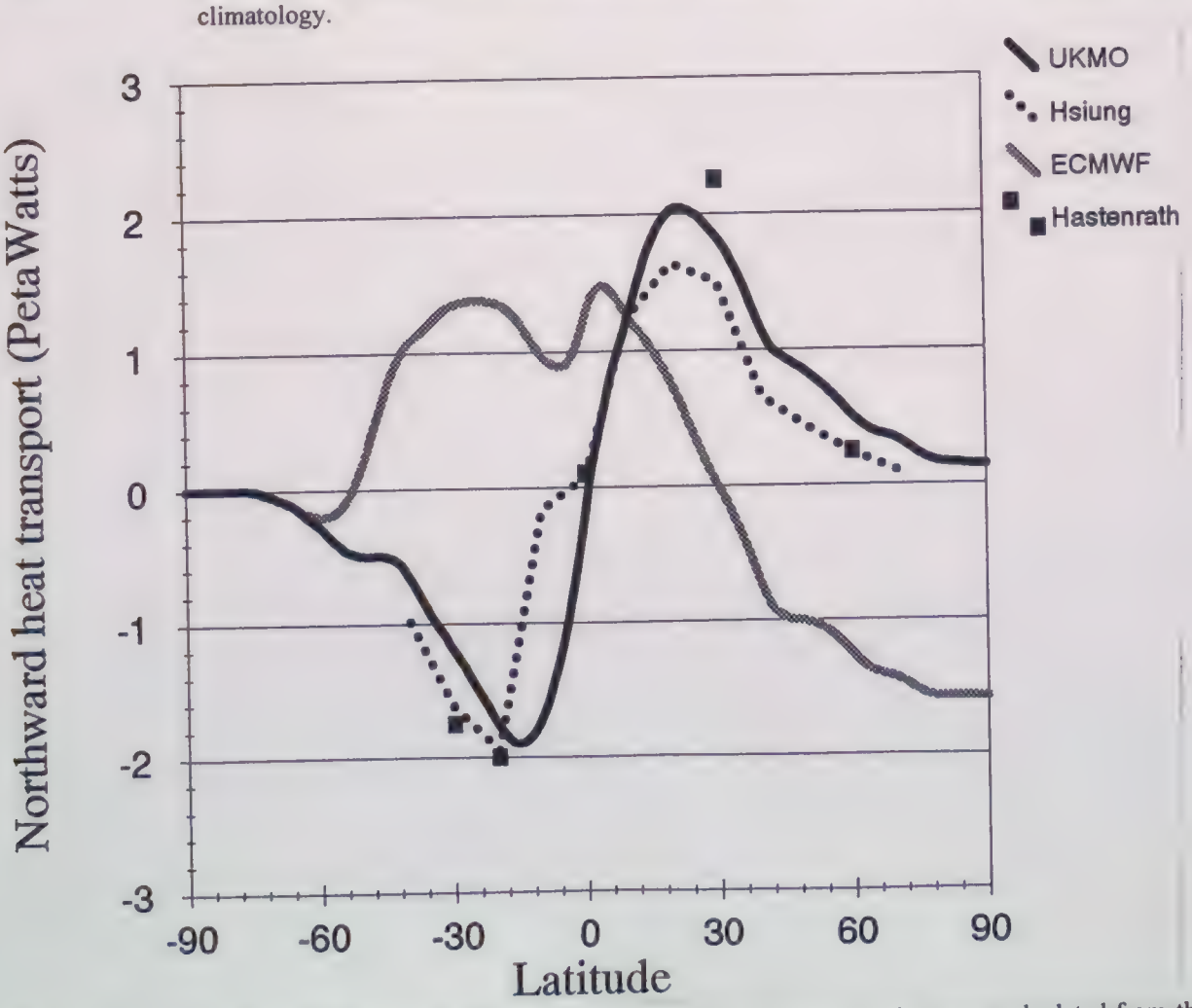

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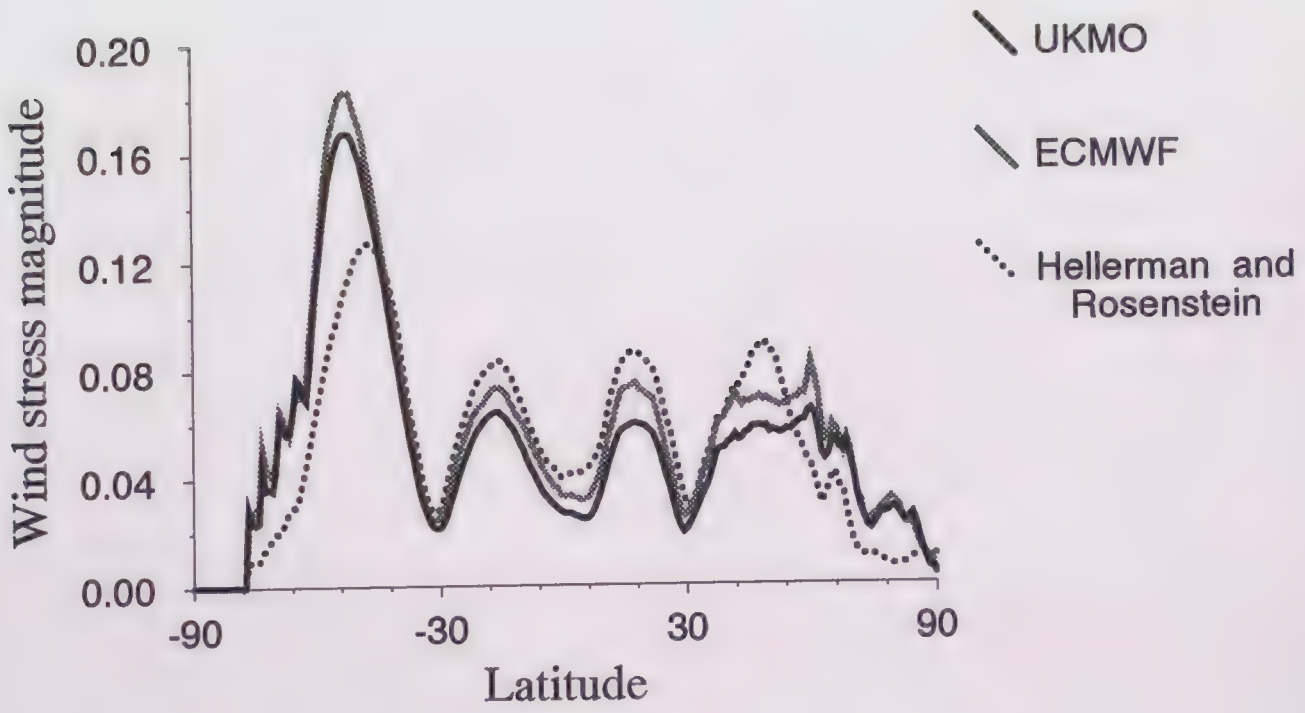

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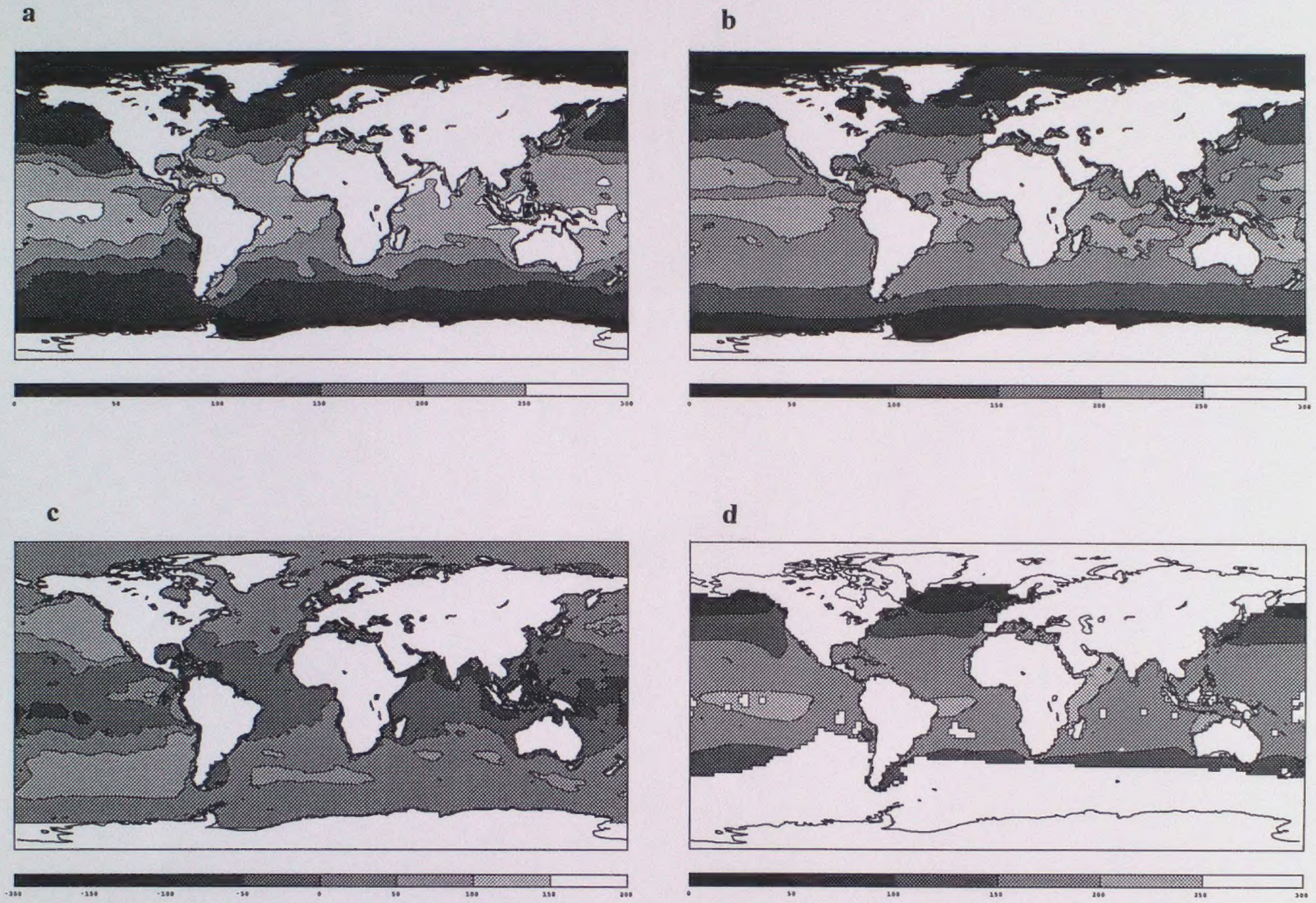

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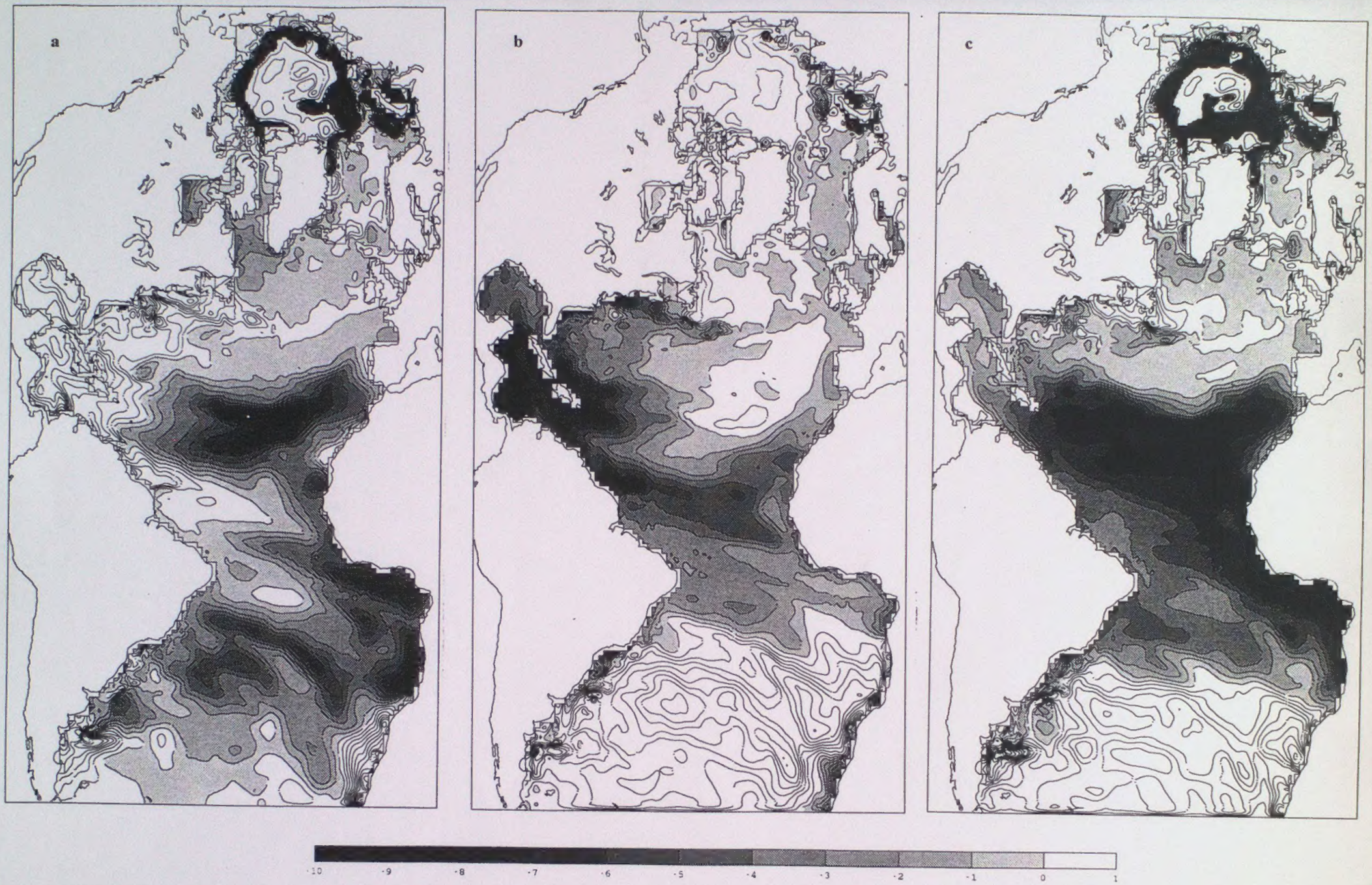

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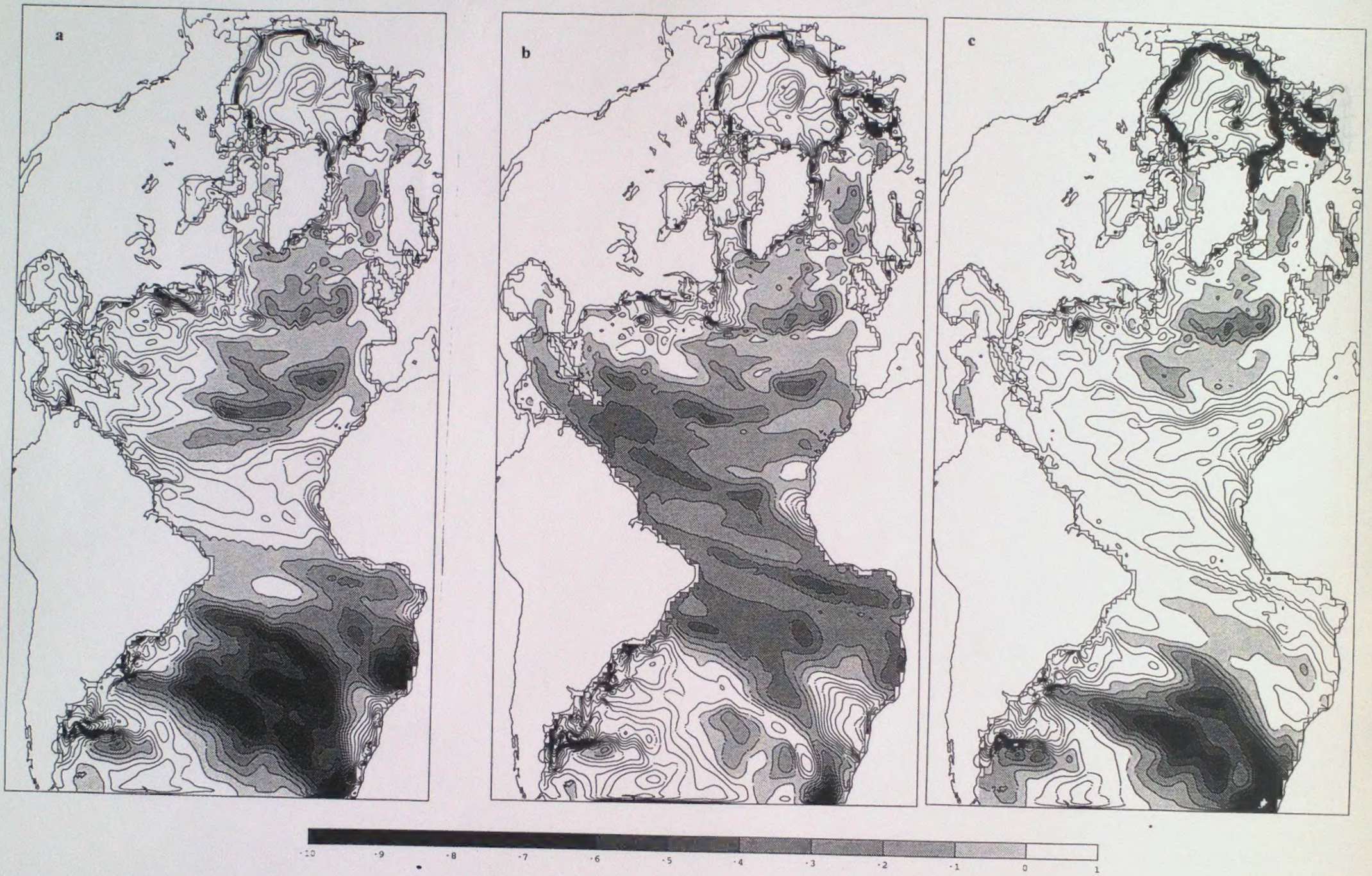

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